

**NASA TECHNICAL
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NASA TM X-52120

NASA TM X-52120

N66-19526

FACILITY FORM 802

(ACCESSION NUMBER)	(THRU)
<u>20</u>	<u>1</u>
(PAGES)	(CODE)
(NASA CR OR TMX OR AD NUMBER)	(CATEGORY)
	<u>03</u>

**BISTABLE FLUID JET AMPLIFIER WITH LOW
SENSITIVITY TO RECEIVER REVERSE FLOW**

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GPO PRICE \$ _____

CSFTI PRICE(S) \$ _____

Hard copy (HC) 1.00

Microfiche (MF) 50

ff 653 July 65

TECHNICAL PREPRINT prepared for Third Fluid Amplification
Symposium sponsored by the U. S. Army Materiel Command
Washington, D. C. , October 26-28, 1965

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION · WASHINGTON, D.C. · 1965

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ABSTRACT

A selected bistable fluid jet amplifier is presented which exhibits low receiver-interaction region coupling and which also has reasonable receiver power recoveries and control signal pressures and flows. The receivers are specifically designed to handle load reverse flow such as might be delivered by a piston. If the control signal pressure is increased approximately 50 percent above that necessary to switch the power jet into an unblocked receiver, the jet may be switched into a receiver pressurized at 40 percent of supply.

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INTRODUCTION

In 1959 and 1960, Diamond Ordnance Fuze Laboratories (now HDL) introduced a series of fluid signal processing devices which were called fluid amplifiers or fluid interaction devices. Unlike the more conventional fluid signal processing devices available at that time, fluid interaction devices possessed no moving mechanical parts and relied instead on the interaction of streams of fluid for their operation. Their simplicity, ruggedness, and lack of moving parts made them appear quite reliable and suitable for use in extreme environments. Potential applications included the use of fluid interaction devices as control components in the vicinity of a nuclear rocket engine, on jet engine inlet and engine controls, and in hot gas servosystems. Considerable interest was aroused in their application and a number of companies and government agencies became active in the field.

Unfortunately, the practical development of useful fluid amplifier circuits proved more difficult than had originally been supposed. The fluid amplifiers of that time were often unstable or noisy when their receivers were blocked, and load-amplifier interactions occurred which were not well understood and degraded system performance. A particular load-amplifier interaction effect which proved quite troublesome was the coupling between a fluid jet amplifier and a blocked, highly capacitive load such as a piston or a bellows. In practical servosystems, however, bellows or piston loads are quite common and their destabilizing effects on fluid jet amplifiers tended to hinder the development of fluid amplifier servosystems.

This paper presents a NASA developed, bistable fluid jet amplifier which was specifically designed to handle such loads and the reverse flow which they can deliver into the receivers of the amplifier. The design presented is still in the developmental stage and needs improvement; however, it is capable of driving a capacitive or reverse flowing load at high speed and with much smaller control signals than would be required of more conventional fluid jet amplifiers under similar loading conditions. It is the purpose of this paper to furnish the designer with an amplifier design which, although in need of refinement, will enable him to apply fluid jet amplifiers in systems where load-amplifier interactions have been heretofore troublesome.

DEVELOPMENT OF A FLUID JET AMPLIFIER CAPABLE OF HANDLING RECEIVER REVERSE FLOW

Description of the Problem

Figure 1 shows a fluid jet amplifier of conventional design driving a dead-ended, highly capacitive load such as a piston. In figure 1(a) the amplifier has been driving the load for a sufficiently long time for all transient effects to die out. If, as shown in figure 1(b), the power jet is switched to the right hand receiver, the volume load will start to discharge. The discharge flow forms a reverse flowing jet which impinges on the power jet in the vicinity of the interaction region. Since the reverse flow initially has a stagnation pressure equal to the maximum static pressure that the amplifier can develop when driving a blocked load, its momentum will keep the main power jet of the amplifier firmly attached to the right-hand wall. In addition, the flow delivered by the reverse flowing jet probably upsets the flow geometry of the interaction region in much the same manner as application of a control signal. Thus, to switch the main power jet back into the reverse flowing receiver, shown in figure 1(c), a control signal much larger than normal must be applied.

Figures 2 and 3 show typical control pressures and flows required to switch a fluid jet amplifier of the design shown in figure 1 into a reverse flowing receiver. As can be seen, the required control pressures and flows rise sharply as a function of the reverse flowing supply pressure of the receiver p_r/p_s . Since this particular fluid jet amplifier design could develop a blocked receiver pressure of 55 percent of the amplifier supply pressure, unduly high control signals are required to assure that it will switch into a highly capacitive load. Otherwise, time must be allowed for the load to discharge to an acceptably low pressure before switching. These restrictions of control signal levels and switching speed considerably limit the usefulness of conventionally designed fluid jet amplifiers as power valves for piston or bellows loads.

Design Approaches

Two conflicting requirements had to be fulfilled to develop a fluid jet amplifier which could handle receiver reverse flow. First, the receiver reverse flow had to be diverted away from the interaction region and, preferably, a quiet ambient atmosphere supplied to the interaction region. Second, the receiver had to develop satisfactory pressure and flow recoveries during normal, forward flowing operation. Both changes in amplifier geometry and the interaction of flow fields could be used to accomplish this task. The former approach was chosen, primarily because of the lack of flow visualization equipment at the time of the amplifier development.

The resultant amplifier design is shown in figure 4. Figure 5 shows an expanded view of the interaction region and inlet portion of the receivers. As can be seen, the receivers in the NASA Model 7 design are pointed away from the interaction region and reverse flow exiting from them will flow out the vents V_3 . The entrance to the vent V_3 is widened slightly so that the extra flow entrained by the reverse flowing receiver jet will be captured and diverted away from instead of into the interaction region. A separate vent V_2 is used to provide entrainment flow to the interaction region. The baffle wall between V_2 and V_3 prevents receiver spillover flow or reverse flow from interfering with the entrainment flow. All vents are connected to atmosphere.

The interaction region (fig. 5) differs somewhat from conventional practice. A set of control port restrictions are used to prevent control flow from entering the interaction region. These control port restrictions have zero offset and are machined in the same pass as the main power nozzle. The use of zero offset enables small machining errors to be self-canceling. Another benefit is that the control flow required by the control port during absence of a control signal is reduced.

Figure 6 shows hypothetical flow patterns in the amplifier receivers during operation. In figure 6(a), the amplifier is driving a conventional orifice load. One portion of the flow is delivered to the load while the other part is exhausted through the vent V_3 . Because the baffle wall isolates the interaction region from the flow going out through the vent V_3 the receiver may be completely blocked with little or no noise occurring on its output.

Figure 6(b) shows operation of the amplifier when one of its receivers is reverse flowing. Because the receiver is directed away from the interaction region, the load reverse flow is dumped out through the vent V_3 . Thus, little interference with the interaction region occurs, and the main power jet may be switched into the reverse flowing receiver by means of a small control signal.

EXPERIMENTAL PERFORMANCE OF NASA MODEL 7 AMPLIFIER

Equipment and Test Procedures

A series of static tests were conducted on the NASA Model 7 amplifier to determine its performance under various loading conditions. Dynamic performance, although important, was not evaluated at this time.

The amplifier (fig. 7) was machined out of an acrylic block by a pantagraph engraving machine. The power throat section was 0.101 centimeter (0.040 in.) wide by 0.152 centimeter (0.060 in.) deep. Wall surface roughness was estimated as being equal or less than 0.0005 centimeter (0.0002 in.) in the vicinity of the power nozzle and interaction region. No particular effort was made to trim the amplifier for symmetrical performance other than exercising suitable care in machining the entire unit. It should be pointed out, however, that the performance of the interaction region is very sensitive to small manufacturing errors, and much difficulty was experienced in trying to machine additional units which yielded the same performance.

Measurements of amplifier triggering pressures and flows as a function of receiver loading were conducted with the test setup shown schematically in figure 8. A servopressure controller was used to maintain either constant positive or negative pressures on one of the two receivers of the amplifier, regardless of the flow through the receiver. Total error in receiver pressure by this method was no greater than 2 percent of the nominal value. The other receiver was optionally loaded with a needle valve or left open to atmosphere. The point of triggering was determined by observing the point at which the trace on the X-Y recorder plot made a sudden break from the previously smooth curve.

Control port cross-flow characteristics were measured with the test setup shown in figure 9. The servopressure controller was again used to maintain atmospheric pressure at the amplifier control port at which the flow was being measured. Thus, a flow resistor with a linear pressure drop-mass flow characteristic could be used to measure control port cross-flow without changing the ambient pressure supplied to the control port.

Receiver characteristics were measured with the setup shown schematically in figure 10. The servopressure controller was again used to maintain the pressure upstream of the linear flow element constant but at a negative pressure equal to the amplifier supply pressure of 6.88×10^3 newtons per meter squared (1.0 psig). Thus, measurements of receiver flow could be made at subambient pressures.

All tests of the Model 7 amplifier were conducted at a supply pressure of 6.88×10^3 newtons per meter squared (1.0 psig) and a temperature of 298° K (75° F).

Sources and Magnitudes of Error

Combined nonlinearity and hysteresis of the pressure transducers and the readout devices were estimated as 1 percent full scale. The nonlinearity of the linear flow elements was also approximately 1 percent of full scale. The transducers, readout device, and the flow element, if applicable, were calibrated as a single unit and in terms of the variable being measured. Estimated calibration accuracy was 1 percent of full scale for pressure measurements and 3 percent of full scale for flow measurements. Reading error, which occurred when switching pressures and flows were read off the X-Y recorder plots, was approximately 0.2 to 0.3 percent of supply pressures and flows to the power nozzle. Total instrumentation and reading error for switching pressures and flows is estimated as being equal or less than 0.4 percent of the amplifier supply pressure and 0.5 percent of its supply flow, respectively. Total instrumentation error for control port cross-flow characteristics is estimated as 0.2 percent of the supply pressure and 0.3 percent of the supply flow, respectively. Total instrumentation and calibration error for the receiver output characteristics is estimated as 2 percent of supply pressure and 4 percent of supply flow.

A set of errors was apparently caused by nonrepeatable variations in the internal flow pattern of the amplifier. The lack of repeatability varied from a minimum for receiver and control port cross-flow characteristics to a maximum when the amplifier was switching into a reverse flowing receiver. In some cases, two distinct triggering pressures were observed. In the other cases, the lack of repeatability is included in the reading error previously discussed.

A variation in performance characteristics was noted from one amplifier to the other. This lack of reproducibility was apparently caused by machining errors and varied from a minimum for receiver pressure flow characteristics to a maximum when control port characteristics were measured. Not enough amplifiers were machined and tested at the time of writing of this report to establish meaningful figures for the observed performance variations; however, preliminary observations indicated that, for carefully machined units, variations in triggering pressures and flow of approximately ± 50 percent or more of the nominal values could be expected. The particular errors in machining which caused these performance variations have not been determined. Nozzle and interaction region wall roughness appear to be major contributors. It was found that any given fluid jet amplifier could be trimmed for symmetrical performance by shaving a small amount of material off the portion of the control port restriction which was in contact with the main power stream. By this procedure, amplifiers could be made with performance characteristics approximately equal to the amplifier reported in this paper. No experiments were performed to find the sensitivity of amplifier performance to variations resulting from photoetching type processes.

DISCUSSION OF RESULTS

Although some coupling between the receiver and the interaction still exists in the NASA Model 7 amplifier (figs. 11 and 12), it is much smaller than the coupling present in an amplifier of more conventional design. A control pressure of only 9 percent of supply pressure was required to switch the particular amplifier tested into a receiver pressurized at 100 percent of supply pressure. The more conventional unit, on the other hand, is practically inoperable after the reverse flowing receiver pressure is above 40 percent of the supply pressure to the main power nozzle. If the receiver pressure into which the main power jet is flowing is increased, the jet attachment becomes more stable and harder to switch (fig. 13). This behavior exists for receiver pressures up to 100 percent of supply and is not typical of amplifiers of the type shown in figure 1.

Figure 14 shows the effects of a "worst possible case" in which the receiver on which the power jet is attached is blocked and the opposite receiver is reverse flowed. As can be seen, a control pressure of 15 percent of supply pressure is adequate to switch the amplifier into a reverse flowing receiver pressurized at 100 percent of supply. In practical situations, it is quite doubtful if such a combination of receiver flows and pressures could be achieved by a damped, second order load such as a piston.

Unfortunately, although the NASA Model 7 fluid jet amplifier has been made relatively insensitive to the effects of receiver return flow, its switching characteristics are strongly affected by a negatively pressurized receiver. Figure 15 shows that a negative receiver pressure of only 15 to 20 percent of supply pressure is sufficient to cause the jet to switch into that receiver. This triggering sensitivity to negative receiver pressure will become important when the amplifier is used to drive a piston. If the amplifier is driving the piston and the piston velocity builds up to a maximum value, the piston could consume a flow of approximately 110 percent of the flow supplied to the main jet power nozzle (fig. 16). However, if the amplifier is switched to the other side to decelerate the piston, the piston will, for a short period of time, continue to draw the same amount of flow out of the receiver. The experimental receiver performance curves shown in figure 16 indicate that a flow of 100 percent of supply out of a receiver will cause a negative pressure of 40 percent of supply if the main power jet is directed towards the other receiver. This negative receiver pressure is sufficient to cause the main power jet to switch back and again accelerate the piston to maximum velocity.

Fortunately, this reverse switching may be avoided if a steady pressure is maintained on the amplifier control ports. Figure 17 shows the control port pressures and flows required to switch the main power jet away from a negatively pressurized receiver and the minimum pressures and flows to keep the jet from switching back (called reverse switching in the figures). As is shown in figure 17, if the negative receiver pressure is less than 50 percent of supply, the control pressures and flows necessary to switch the jet away from a negatively pressurized receiver are more than enough to keep it away. A negative receiver pressure of 50 percent of supply will

correspond to a flow greater than the amplifier was capable of delivering to the piston load and hence is not likely to be encountered in a non-resonant load. Consequently, if the driver stage used to drive the Model 7 amplifier maintains continuous pressures and flows in the amplifier control ports, the Model 7 amplifier would not be expected to switch because of the negative receiver pressures created by piston deceleration.

Figure 17 also shows the presence of two distinct triggering pressures. The pressure at which the amplifier would switch appeared to be a function of how rapidly the control signal was applied.

A combination of receiver loads not investigated was a negative receiver pressure on the side on which the jet was attached and a positive pressure (hence implying reverse flow) on the side toward which the jet was being switched. However, omission of this combination of loads is not expected to be serious since both are not likely to occur at the same time. If a piston load is being driven by the amplifier, maximum receiver pressure will be developed only when the piston is moving very slowly and hence drawing very little flow. Conversely, maximum flow will be drawn by the piston only when the pressure differential across it is a minimum. Hence the conditions of most difficult switching are probably given by either figures 11 and 12, or figure 17.

The control port cross-flow characteristics of the amplifier are shown in figure 18. As is seen, flow entrainment into the control port is low during the absence of a control signal. Control port cross flow does not start to become significant until a control pressure in excess of 5 percent of supply is applied to the opposite control port. A control port pressure of 10 percent of supply, which is sufficient to cause the amplifier to switch under practically any piston load, causes a control port cross flow of only 4 percent of supply. This value of cross flow is quite low and can probably be handled without difficulty by most passive or active fluid logic elements of conventional design (cf., fig. 1).

CONCLUSIONS

It is concluded that a bistable fluid jet amplifier with reasonable receiver pressure and flow recoveries can be made which exhibits greatly reduced sensitivity to receiver loading effects. The design is particularly good at handling receiver reverse flow, such as might be delivered by a piston and bellows, and should find application for such loads. At the supply pressure tested (1.0 psig), application of continuous control pressures and flows of 15 and 10 percent of supply, respectively, are sufficient to enable the amplifier tested to drive a piston load under most conceivable modes of operation.

The design is not yet optimized, and it is concluded that the performance of the interaction region is sensitive to small manufacturing errors. Any particular amplifier may be trimmed to give symmetrical performance,

after which it will continue to give reproducible results. However, a new interaction region design must be developed which will give the necessary jet deflection angles, have short length, and exhibit reduced performance sensitivity to the manufacturing process. One possibility is the more conventional interaction region shown in figure 1.

The design presented in this paper is basically incompressible and will not work well at supply pressures approaching critical or greater. Work should be done to develop an amplifier with a supersonic nozzle which can operate at more useful supply pressures.

NOMENCLATURE

D_j width of main power nozzle, m (in.)
 h height of channels in fluid jet amplifier, m (in.)
 \dot{m} mass rate of flow, kg/sec (lb_m/sec)
 p pressure, N/m^2 ($\text{lb}_f/\text{in.}^2$) gage

Subscripts:

c control
 r receivers
 s supply conditions
 v vent

Superscript:

$^\circ$ angle, deg

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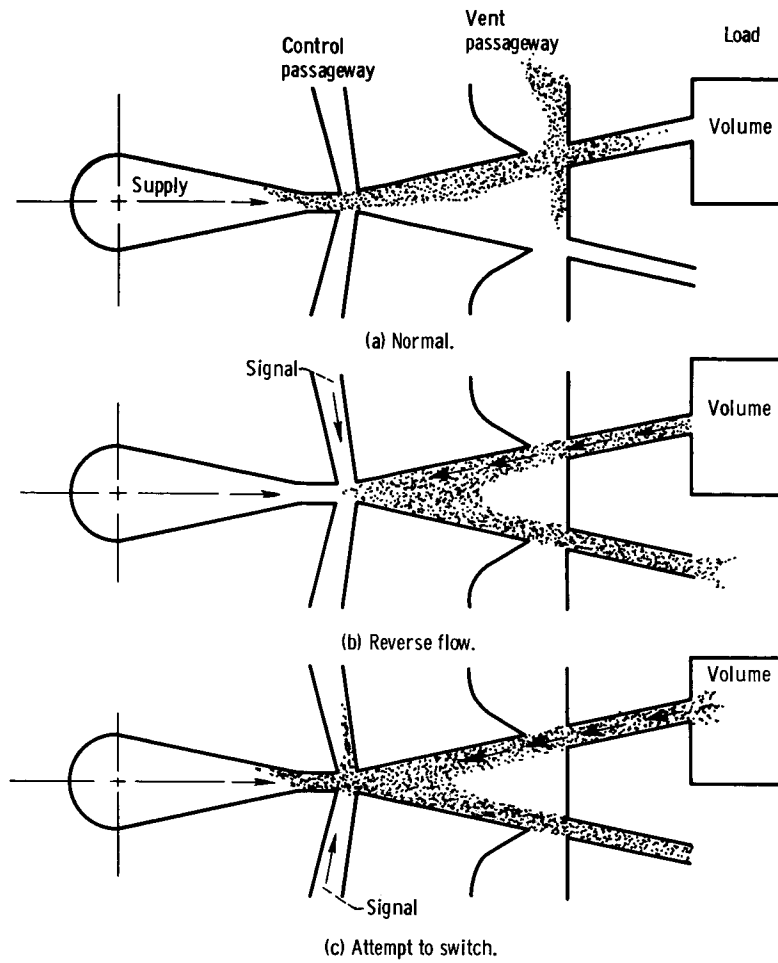


Figure 1. - Performance of standard design bistable element with various receiver loadings.

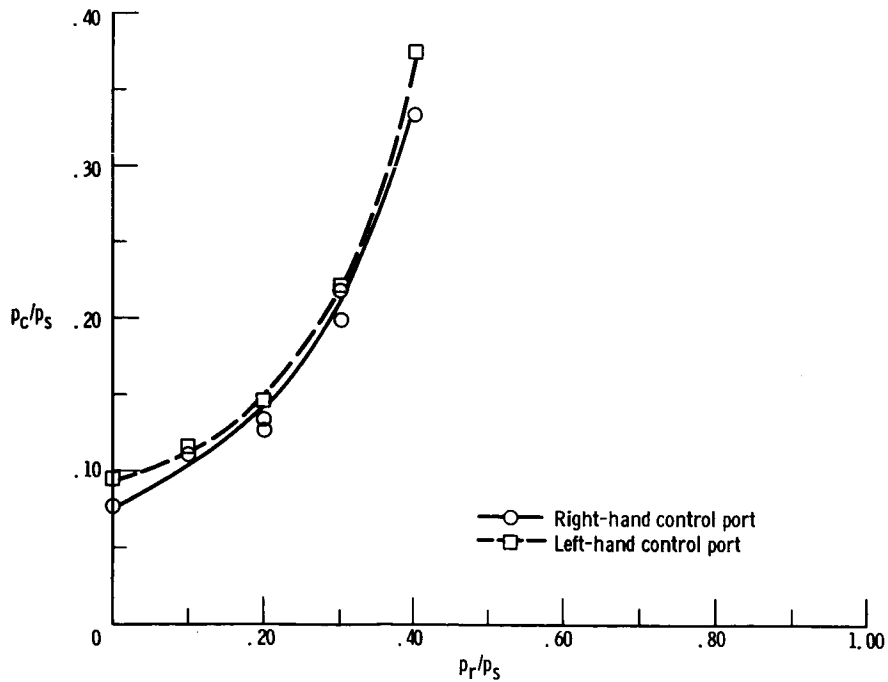


Figure 2. - Control pressures required to switch conventional fluid jet into reverse flowing receiver. Other receiver is vented to atmosphere.

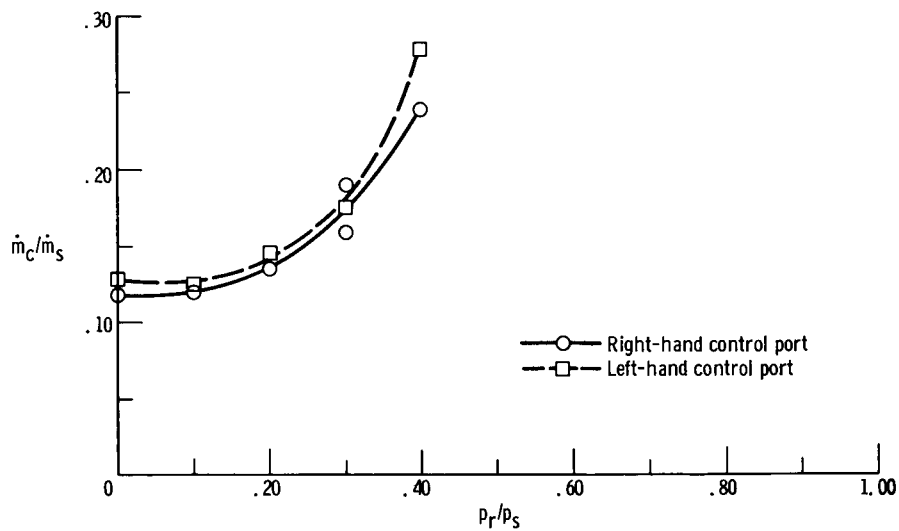
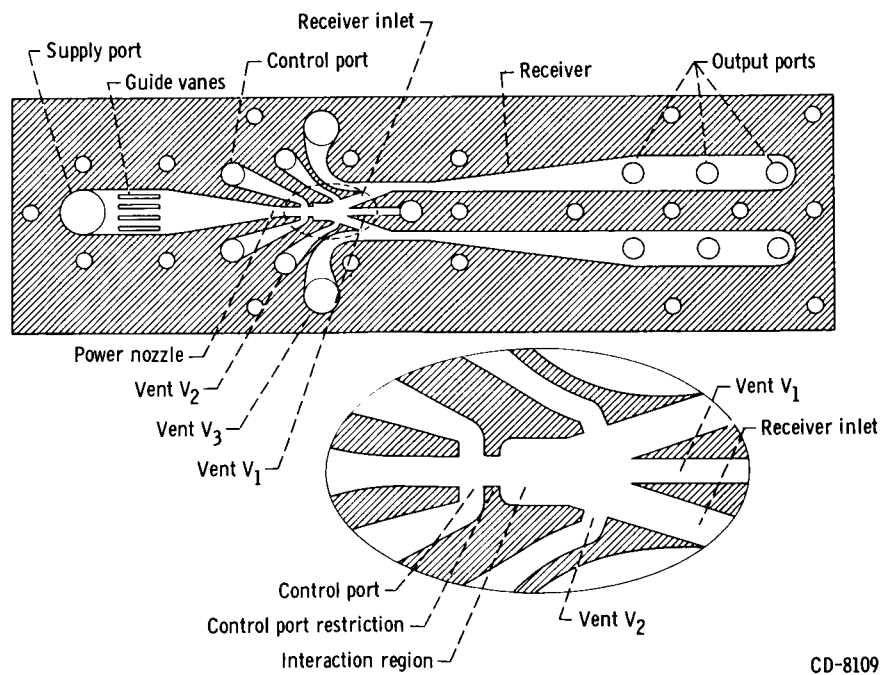


Figure 3. - Control flows required to switch conventional fluid jet amplifier into reverse flowing receiver. Other receiver is vented to atmosphere.



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Figure 4. - NASA Model 7 fluid jet amplifier.

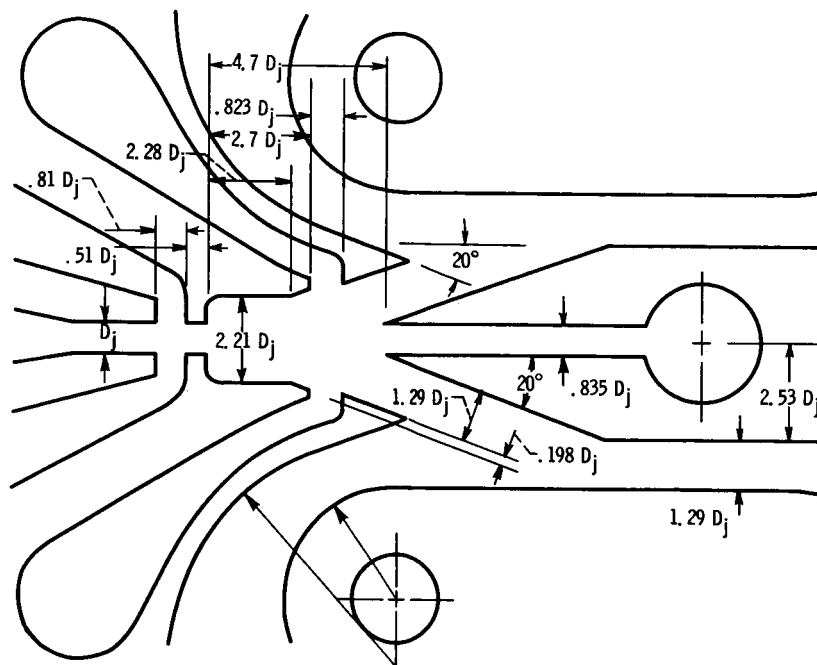
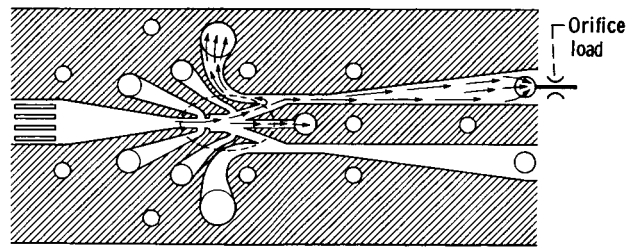
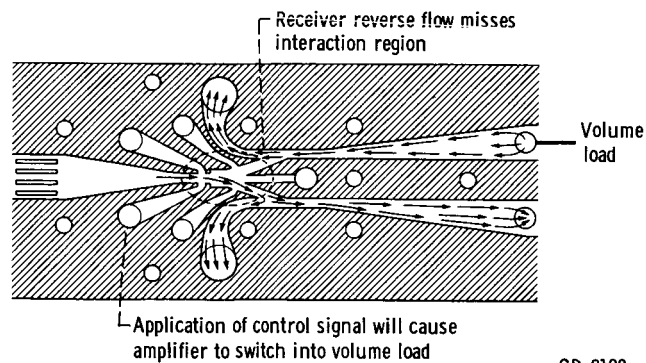


Figure 5. - Interaction region of NASA Model 7 fluid jet amplifier.



(a) Normal, forward flowing operation.



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(b) Operation when receiver is reverse flowing.

Figure 6. - Performance of the NASA Model 7 fluid jet amplifier under various loading conditions.

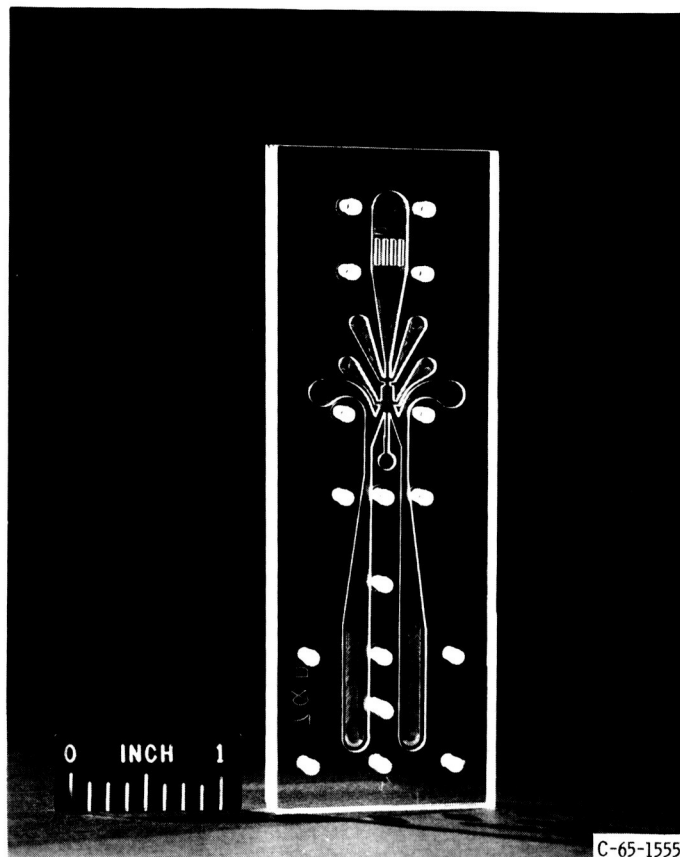


Figure 7. - NASA Model 7 fluid jet amplifier.

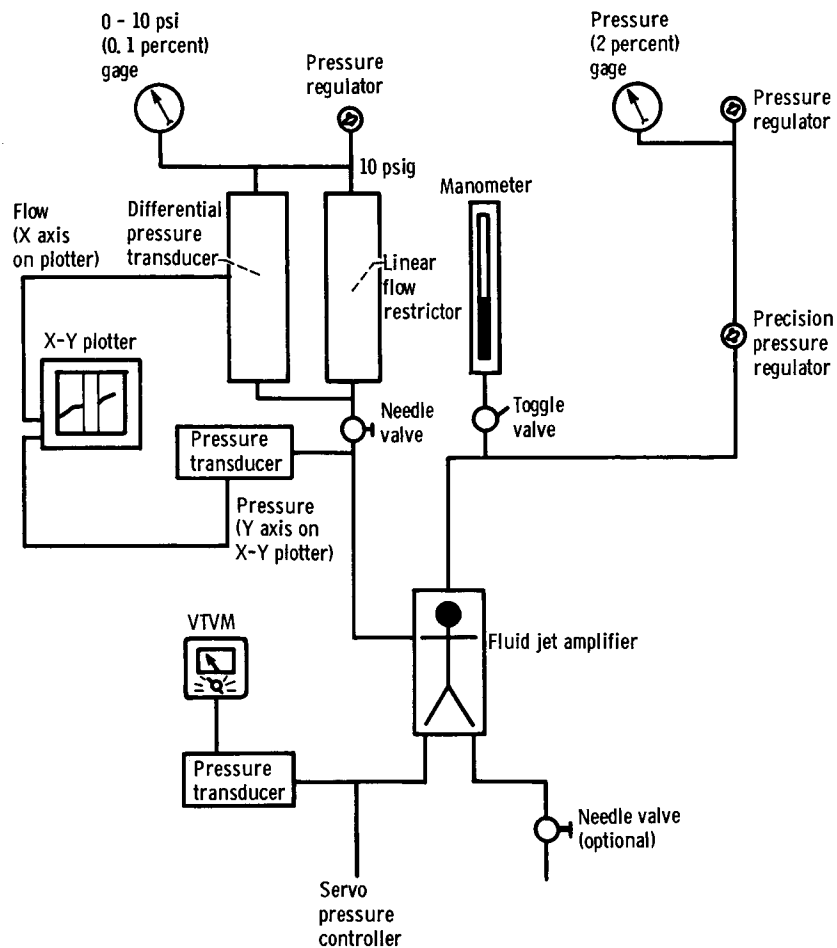


Figure 8. - Schematic of test to measure control port switching pressures and flows.

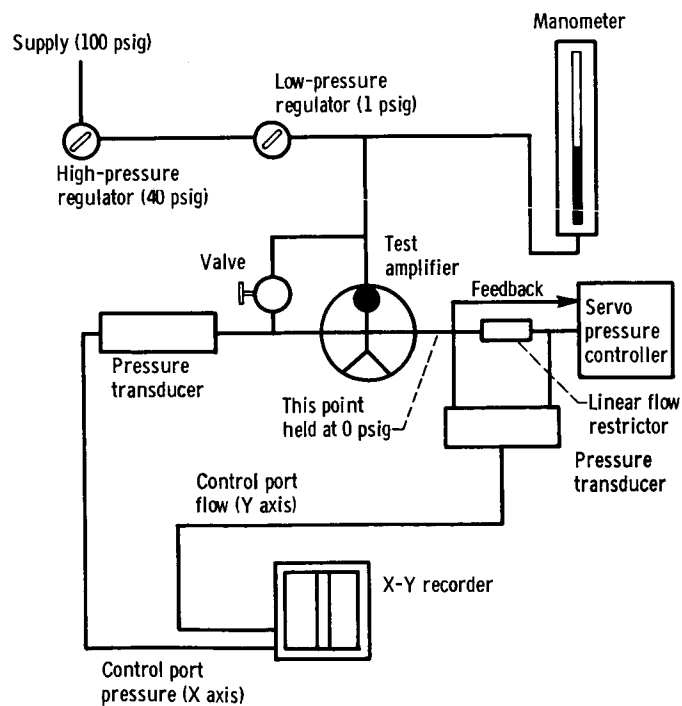


Figure 9. - Schematic of test to measure control port crossflow characteristics.

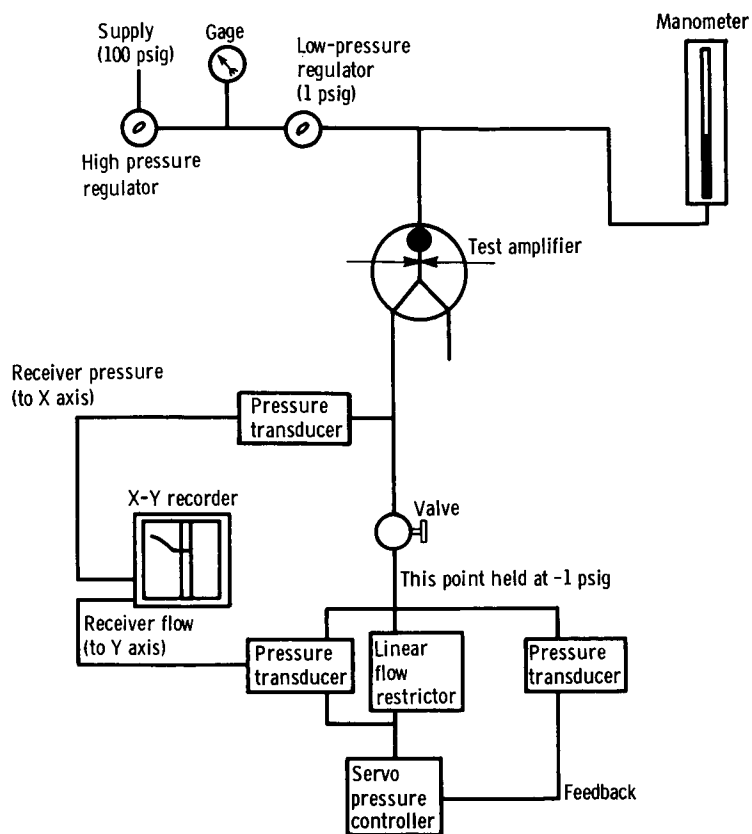


Figure 10. - Schematic for test to measure receiver characteristics.

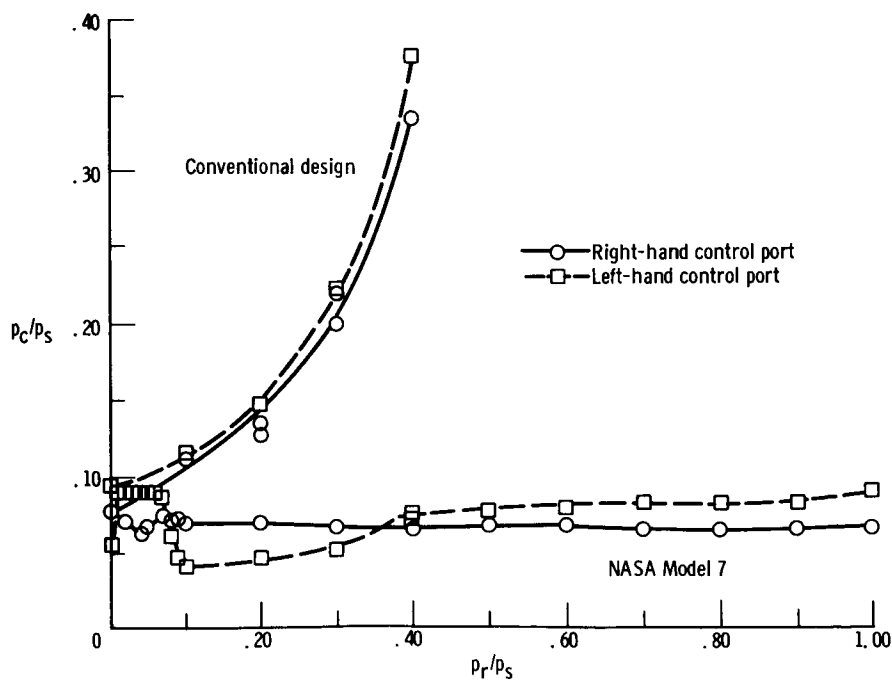


Figure 11. - Control pressures required to switch conventional and NASA Model 7 fluid jet amplifiers into reverse flowing receivers. Other receiver is vented to atmosphere.

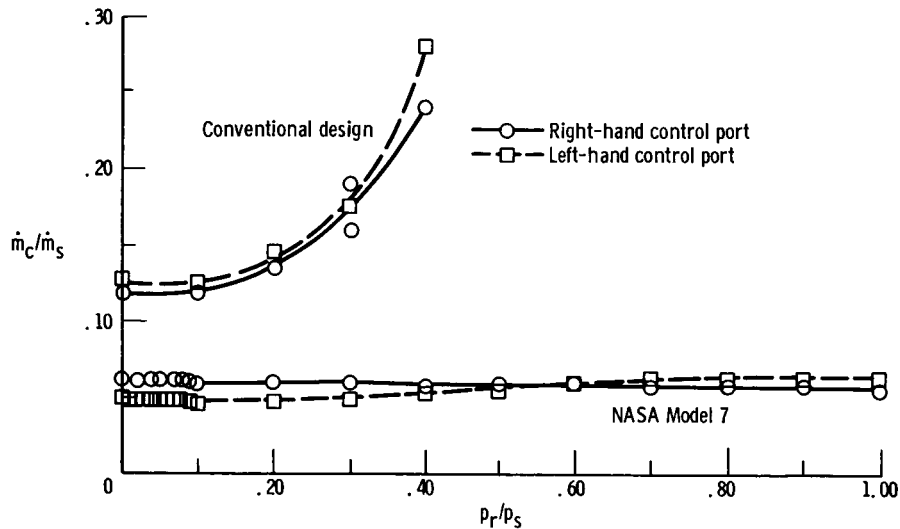


Figure 12. - Control flows required to switch conventional and NASA Model 7 fluid jet amplifiers into reverse flowing receivers. Other receiver is vented to atmosphere.

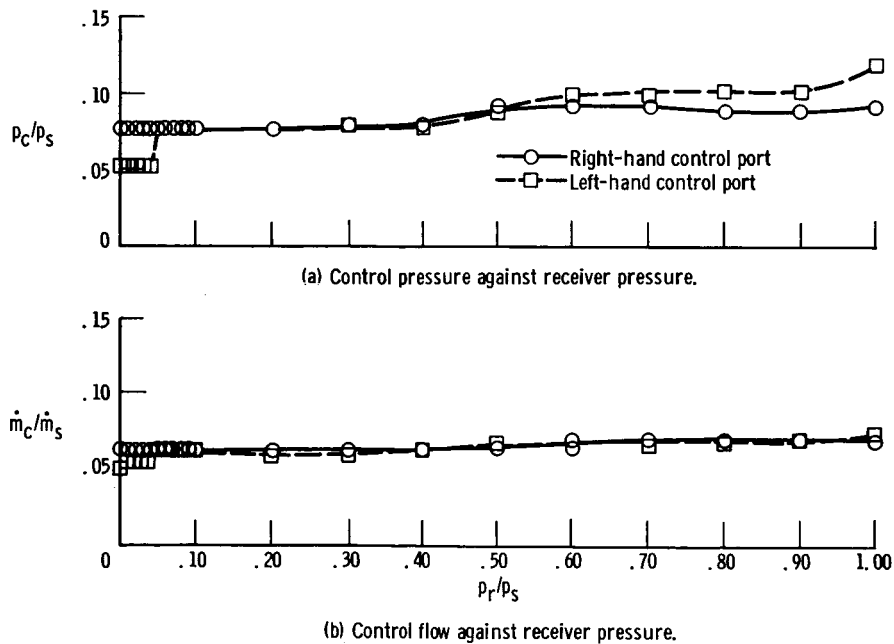


Figure 13. - Control pressures and flows required to switch NASA Model 7 fluid jet amplifier away from pressurized receiver. Other receiver is vented to atmosphere.

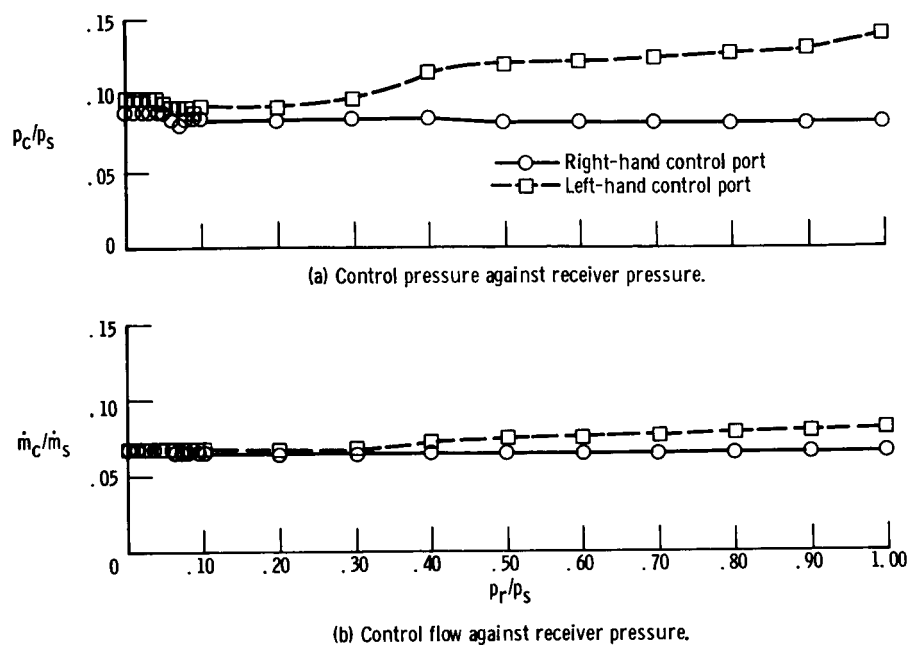


Figure 14. - Control pressures and flows required to switch NASA Model 7 fluid jet amplifier into reverse flowing receiver. Other receiver is blocked.

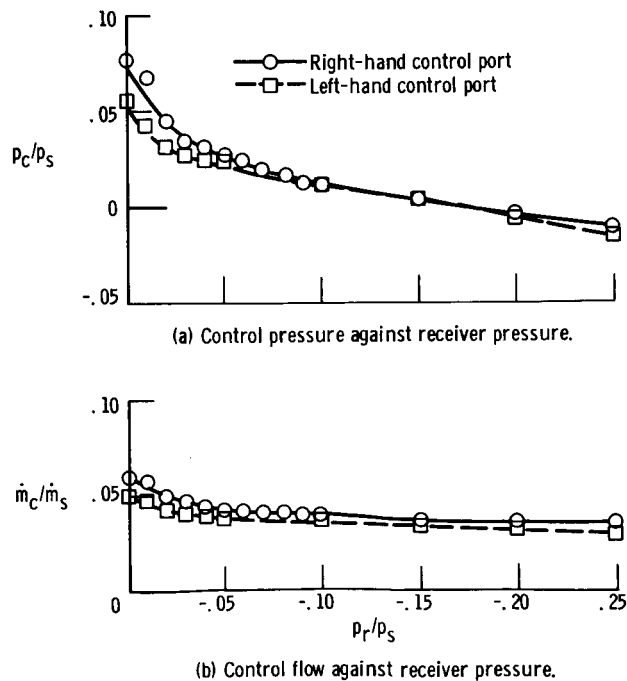


Figure 15. - Control pressures and flows required to switch NASA Model 7 fluid jet amplifier into a negatively pressurized receiver.

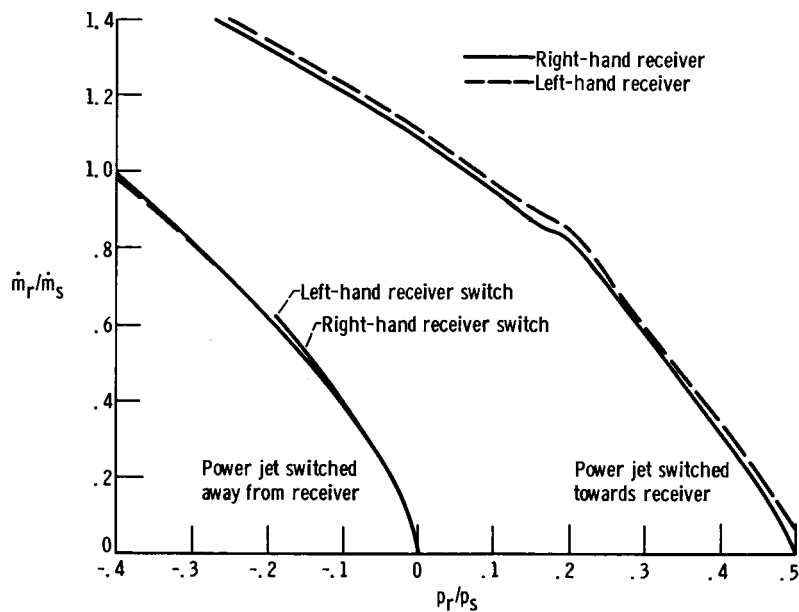


Figure 16. - NASA Model 7 fluid jet amplifier receiver pressure-flow characteristics.

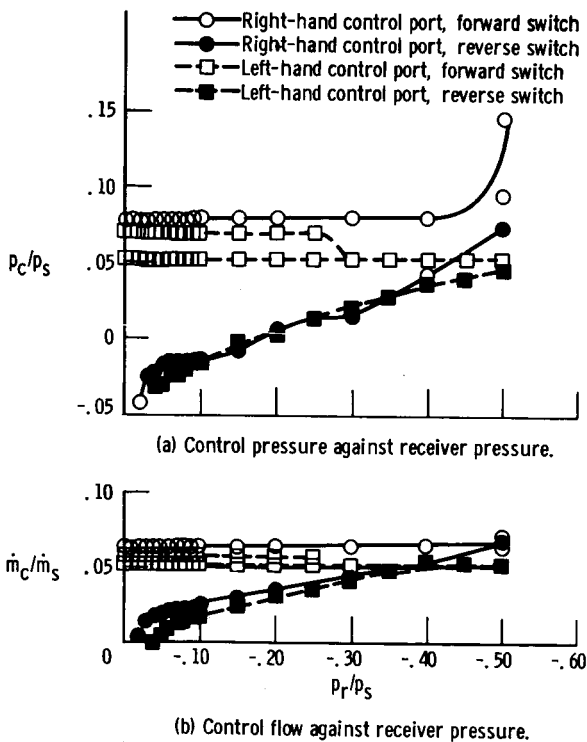


Figure 17. - Control pressures and flows required to switch NASA Model 7 fluid jet amplifier away from negatively pressurized receiver.

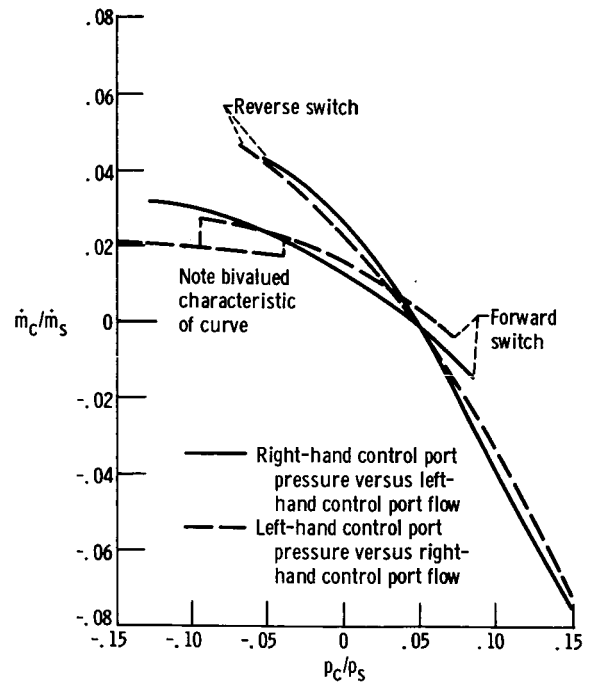


Figure 18. - NASA Model 7 fluid jet amplifier control port cross flow characteristics.